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SUMMARY

The flashback and blowoff stability limits of the gaseous, premixed, stoichiometric, turbulent cyanogen-oxygen flame were determined at pressures from 40 to 200 lb/sq in. abs (about 3 to 14 atmospheres) by using four different burner sizes. The stability characteristics for flashback and blowoff were correlated by the critical-boundary-velocity-gradient theory.

The pressure exponent of the critical flashback boundary velocity gradient was 1.97 and the pressure exponent for blowoff was 1.85. Comparison with reference data showed that the temperature of the atmosphere surrounding the flame had little effect on flashback.

These results are compared with reference data obtained at pressures from 1 to 5 atmospheres. Included in the appendix are some data obtained at pressures from 0.01 to 0.1 atmosphere.

INTRODUCTION

In order to develop a means for producing high-temperature, high-enthalpy, fluid flows of long duration, experiments have been conducted with the premixed, gaseous, stoichiometric cyanogen-oxygen flame. This flame is one of the hottest of all known flames. At atmospheric pressure and a gas temperature of 298° K the flame temperature of the equimolar reaction has been calculated to be 4,850° K (refs. 1, 2, and 3) and has been experimentally measured as 4,640 ± 200° K (ref. 4). The high temperature of the cyanogen-oxygen flame is due to the high thermal stability of the combustion products (which are carbon monoxide and nitrogen); heat liberated by the reaction goes mainly into raising the temperature of the products and very little towards dissociating them. Increasing pressure depresses the degree of dissociation and results in a still higher flame temperature. At a pressure of 10 atmospheres, the flame temperature has been calculated to be 5,050° K (ref. 5); the computed flame temperature for no dissociation (pressure greater than 40 atmospheres) is about 5,210° K.

Carbon monoxide and nitrogen are isosteric; this similarity results in a mixture which behaves thermodynamically as if it were all nitrogen. Thus, the combustion products can be considered to resemble air without the oxygen component. For many considerations, this similarity to air, along with the high temperature of the combustion products, makes the cyanogen-oxygen flame very attractive as a research tool. The premixed cyanogen-oxygen flame at 1 atmosphere has been extensively studied at the Research Institute of Temple University (refs. 3 and 4), where flame stability measurements have been made at pressures up to 5 atmospheres (ref. 5). The flame has also been used at Temple University to study the effect of high temperature on materials (ref. 6). Recently, the cyanogen-oxygen flame at 1 atmosphere has been used to provide a plasma source for the study of the problem of radio-frequency signal attenuation through plasmas (ref. 7).

The use of the high-temperature combustion products in a hypersonic tunnel is desirable in order to produce test-section temperatures similar to ambient flight temperature. In order to utilize the combustion products as the working fluid of a hypersonic tunnel, however, the combustion must take place at high pressure so that the test-section pressure also may be of the order of the ambient flight pressure. For example, to produce a flow with a Mach number of 10 at free-stream temperature and pressure corresponding to an altitude of 160,000 feet, it is necessary to burn the cyanogen-oxygen mixture at a total pressure of about 100 atmospheres.

In order to design the fuel-oxidant injection system and the combustion chamber for this high-pressure system, it was first necessary to study the stability characteristics of the premixed stoichiometric cyanogen-oxygen flame at high pressure. These flame-stability characteristics are the pressure limits (for a given mixture velocity and burner diameter) at which the flame becomes unstationary at the burner rim. One limit, which is called flashback, is that pressure at which the propagation velocity of the flame becomes large enough, relative to the gas inflow velocity, to cause the flame to move upstream into the burner tube. The other limit, which is referred to as blowoff, is that pressure at which the flame ceases to propagate at a sufficient velocity, relative to the gas inflow velocity, to remain at the burner rim. The stability data of reference 5 (which are presented herein for comparison) pertain to the flashback stability limit of the premixed cyanogen-oxygen flame up to a pressure of 5 atmospheres, and are primarily concerned with the laminar flame. The additional stability information furnished by the present work is in the turbulent flow regime and at pressures higher than 5 atmospheres, so that extrapolation of these flame-stability data to the working pressure of such a hypersonic tunnel would yield more reliable information. This paper presents flashback and blowoff stability characteristics of the turbulent, premixed, gaseous cyanogen-oxygen flame in the pressure range of 40 to 200 lb/sq in. abs (approximately 3 to 14 atmospheres).

Also presented, in the appendix, are stability data for the premixed, stoichiometric cyanogen-oxygen flame in the very low-pressure regime from 0.01 to 0.1 atmosphere. These flashback and blowoff flame-stability data were obtained in the design of a low-pressure plasma source. The data are presented for completeness, so that flame-stability information for the cyanogen-oxygen flame may be available over the largest possible pressure range.

SYMBOLS

A	burner flow area, sq ft
D	burner flow diameter, ft
f	friction factor, $\tau_w \big/ \frac{1}{2} \rho \overline{V}^2$
g	boundary velocity gradient, $\left(\frac{dV}{dy}\right)_w$, sec^{-1}
g^*	critical boundary velocity gradient at flashback or blowoff, sec^{-1}
l	length of burner tube, ft
M	molecular weight, slugs/slug-mole
R	Reynolds number, dimensionless
p	pressure, psia
t_m	temperature of gas mixture, ^{o}F
w	mass flow, slugs/sec
y	distance from burner wall, ft
x	mole fraction, dimensionless
V	velocity, ft/sec

ϕ_{ij}	function defined by equation (9)
ρ	mass density, slugs/cu ft
τ	shearing stress, lb/sq ft
μ	coefficient of viscosity, lb-sec/sq ft

Subscripts:

fb	flashback
bo	blowoff
w	wall
o	reservoir
1	diffusing component
2	basic component

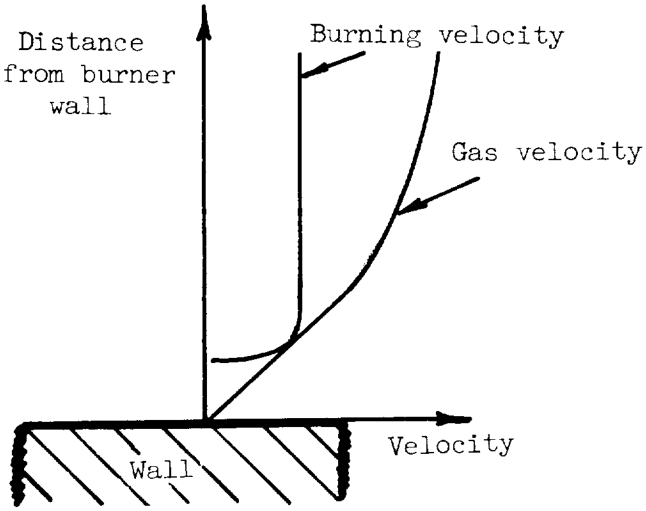
A bar over a symbol denotes the average value.

FLAME-STABILITY THEORY

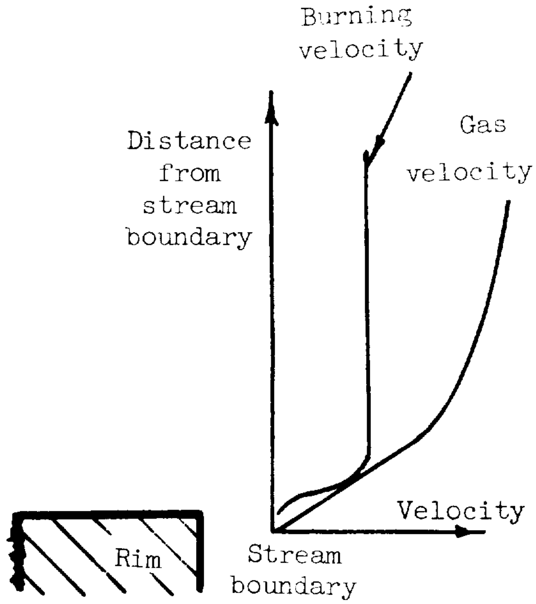
Flow Model

In real-gas flow there is a velocity gradient near a boundary wall due to viscous retardation. In this retarded-flow region the velocity of the gas ranges from zero at the wall to the free-stream velocity at a distance from the wall known as the boundary-layer thickness. There is also a gradient in the burning velocity of a flame close to a burner wall. At the wall (which is usually cold relative to the flame) the burning velocity is zero because of the large decrease in temperature of the fluid mixture caused by heat transfer to the wall (quenching effect). As the distance from the burner wall increases, the burning velocity of a flame becomes larger because of the increased fluid temperature and the consequent increased concentration of the chemically active chain carriers in the flame.

In the following sketches are shown, qualitatively, the gas velocity and burning velocity distributions for a stable flame near the flashback and blowoff stability limits.



Sketch A - Near flashback



Sketch B - Near blowoff

Sketch A represents the case of a flame stabilized near the wall of a burner tube. The dimensions shown are considered small compared to the diameter of the burner tube so that the gas flow near the wall is laminar, and the gas-mixture velocity gradient is almost linear. Near the flashback condition a flame is stabilized at a distance from the burner wall where the burning velocity just equals the gas-mixture velocity. At no point along the flame front can the burning velocity exceed the local gas-stream velocity if the flame is to remain stable. Reducing the gas flow (below that shown in sketch A) reduces the velocity of the gas stream near the burner wall and thus allows the burning velocity, at some point on the flame front, to become greater than the gas-stream velocity. This situation causes the flame to flash back into the burner tube.

Increasing the gas flow (greater than that shown in sketch A) so that the velocity of the gas mixture becomes greater than the burning velocity everywhere along the flame front causes the flame to move downstream out of the burner. The flame cannot be maintained in the burner tube at this increased gas-mixture velocity but a new stable position may be attained beyond the burner rim, as shown in sketch B. At this new position, the burning-velocity curve can more closely approach the stream boundary since there is less heat transfer, and hence the mixture can reach a higher temperature near the boundary when the flame is stabilized downstream of the burner rim. The condition for a stable flame can again be met at this position - that is, the burning velocity is just equal to the gas-mixture velocity at some equilibrium distance from the stream boundary, and at no point along the flame front does the burning velocity exceed the gas-mixture velocity. The flame may be maintained over a range of downstream positions by the stabilizing nature of the burner wall; upstream movement of the flame front (caused by a small decrease in flow velocity) is stabilized by increased quenching near the wall, and downstream movement (due to a small increase in flow velocity) is stabilized by both decreased wall quenching and diminishing gas velocity in the boundary due to mixing. As the distance from the flame front to the burner rim increases, a point is reached where intermixing of the gas mixture with the atmosphere surrounding the flame influences the burning velocity (ref. 8) and hence becomes an important consideration; that is, the flame front may be driven to a distance from the burner rim where intermixing has a greater effect on the burning velocity than the decreased heat transfer. If the burning velocity is less than the gas-mixture velocity everywhere along the flame front, the flame will be blown off the burner tube (ref. 9).

Critical-Boundary-Velocity-Gradient Theory

Combustion investigators have been unable analytically to relate flame velocity to the aerodynamic, thermodynamic, and chemical properties of the gas mixture to any quantitative extent because of the complexity and the many uncertainties involved. Some success has resulted, however, from the use of correlating parameters (or similarity parameters) to characterize the combustion regimes. One such parameter which has proven useful for correlation of flame-stability data over a range of burner sizes, mixture flow conditions, and pressure levels is referred to as the "boundary velocity gradient." This is the velocity gradient of the gas at the burner wall (for fully developed flow), and its value just at the condition of flashback (or blowoff) is called the "critical boundary velocity gradient." (See ref. 9.) It is this boundary velocity gradient with which the present work is concerned in studying the stability characteristics of the cyanogen-oxygen flame.

In taking into account the dependence of the velocity gradient of the gas mixture on the stream properties, an equation for the boundary velocity gradient is derived in terms of Newton's shear-stress equation and the friction factor (ref. 9):

$$g = \frac{dV}{dy} \tag{1}$$

$$\tau_w = \mu\left(\frac{dV}{dy}\right)_w = \frac{1}{2} f\rho\bar{V}^2 \tag{2}$$

$$g = \frac{\frac{1}{2} f\rho \overline{V}^2}{\mu} = f \frac{\overline{V}}{2D} R \qquad (3)$$

From the classical equations for fully developed, constant-property, laminar pipe flow, the friction factor is found to be $16/R$. The equations for fully developed turbulent pipe flow are too complicated to yield a solution. Experimentally, however, the friction factor was found to be $0.046/R^{0.2}$ in the Reynolds number range of 5,000 to 200,000 (ref. 10).

When the flame is about to flash back, $g = g^*_{fb}$, and substituting the values for friction factor into equation (3) yields for laminar flow

$$g^*_{fb} = \frac{8\overline{V}_{fb}}{D} \qquad (4)$$

and for turbulent flow

$$g^*_{fb} = \frac{0.023}{D} R^{0.8} \overline{V}_{fb} \qquad (5)$$

where the average mixture velocity is

$$\overline{V} = \frac{w}{A\rho} \qquad (6)$$

and the Reynolds number is

$$R = \frac{\rho \overline{V} D}{\mu} \qquad (7)$$

Although for the case of blowoff the concept of a boundary velocity gradient is not as straightforward as for the case of flashback, the same relationships, when applied to g^*_{bo}, have been found to correlate the blowoff data. The viscosity μ of the cyanogen-oxygen mixture was calculated by using the following equation (ref. 11):

$$\mu = \frac{\mu_1}{1 + \frac{x_2}{x_1} \phi_{12}} + \frac{\mu_2}{1 + \frac{x_1}{x_2} \phi_{21}} \qquad (8)$$

where

$$\phi_{ij} = \frac{\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2}\left(\frac{M_j}{M_i}\right)^{1/4}\right]^2}{\frac{4}{\sqrt{2}}\left(1 + \frac{M_i}{M_j}\right)^{1/2}} \tag{9}$$

APPARATUS AND PROCEDURE

Figure 1 is a schematic diagram of the high-pressure assembly. Safety considerations led to locating the combustion chamber and cyanogen reservoir inside a steel and sand-bagged shelter. It was found, however, that except for its toxicity, cyanogen posed no more problems than any other combustible gas.

Combustion Chamber and Burner

The stainless-steel combustion chamber, shown in figure 2, was cylindrical and was water cooled. Its inside diameter was 3 inches and it had an overall length of 24 inches. The burners were fabricated of copper and also were water cooled. They were $2\frac{1}{2}$ inches long and had an outside diameter of 7/8 inch. Since the mass flow of the system was limited by the flowmeters, high gas-stream velocities were obtained by the use of small burner-opening diameters. Four different burner diameters were used: 0.1 inch, 0.094 inch, 0.074 inch, and 0.052 inch. These were obtained either by fabricating a completely new burner or by filling the old one with silver solder and drilling the new dimension. The burner tip was viewed through a pyrex window and a system of mirrors. To protect the apparatus, a blowout diaphragm was set to rupture at approximately 1,000 lb/sq in.

Gas Supply System

To achieve the operating pressure of the experiments, it was necessary to raise the temperature of the cyanogen. Therefore, the cyanogen reservoir was placed inside a steam-heated tank and heated until its vapor pressure reached the predetermined desired value. To prevent subsequent cyanogen condensation, the vapor feed lines were steam jacketed. Also, the cyanogen flowmeter was located in a heated tank and maintained at the same temperature as the reservoir. The oxygen was metered at reservoir pressure and ambient temperature and then was heated by passing it through a tubular coil placed in the hot reservoir. The oxygen feed lines were also steam jacketed in an effort to maintain the same temperature for both gases.

Measurements

The cyanogen and oxygen flow rates were measured by armored, variable-area, tube-type flowmeters. The necessary calibrations for these gages were obtained from data supplied by the manufacturer. Bourdon pressure gages were used to measure the pressure of both the cyanogen and oxygen before mixing and the pressure of the reaction products within the combustion chamber. Thermocouples measured the burner-tip temperature and the temperature of the gases at the flowmeters and in the mixing chamber. These temperatures were found to remain unchanged during a specific run.

Procedure

Before each run the feed lines and combustion chamber were thoroughly purged with nitrogen. An acetylene-air torch was placed in the ignition port to initiate the flame. The torch remained in the ignition port until the flow rates of both the cyanogen and the oxygen reached their predetermined values. It was found easier to allow the oxygen to reach its required flow first and then to "bring up" the cyanogen until the mixture reached stoichiometric proportions. After the ignition port was closed, pressure inside the chamber was increased by throttling the products of combustion with the exhaust valve. This reduced the velocity of the gas mixture and caused the flame front to travel upstream until it reached a relatively stable position on the burner tip.

Blowoff was achieved by reducing the chamber pressure slowly until the flame lifted off the burner and disappeared from sight. Flashback was obtained by increasing the pressure and thus reducing the incoming gas flow velocity to such a point that the flame traveled back into the burner tube.

RESULTS AND DISCUSSION

The experimentally determined flashback and blowoff velocities at the various pressures, burner diameters, and mixture temperatures are listed in table I.

Flashback

The values of critical flashback gradient were calculated by use of equation (5) and are presented in figure 3 plotted against combustion chamber pressure. The pressure exponent of the critical flashback gradient $\frac{\partial \log g^{*}_{fb}}{\partial \log p}$ has been found to be of significance (see ref. 12) in terms of the chemical kinetics of the flame reaction. This exponent was found to be 1.97 for the cyanogen flame, by taking the average of the slopes of the groups of data points obtained from each burner. The curve was then drawn with this slope to include the greatest number of data points.

It is apparent from figure 3 that while the critical-boundary-velocity-gradient theory correlates the data obtained from each individual burner as to slope, the value of the curve of g^{*}_{fb} may have some additional dependence on burner-tube diameter. It appears, furthermore, that the additional dependence on diameter becomes more pronounced at the lower values of g^{*}_{fb}, although additional data would be needed to verify these suppositions. These effects would not seem to be explained by a flow transition (from laminar to turbulent flow) on the basis of pipe Reynolds numbers, which are all above 10,000. Neither would the effects be attributed to the presence of a non-fully-developed pipe flow as the length-diameter ratios are about 25 or greater. However, as no cold flow surveys were made, the aforementioned possibilities cannot be excluded.

Blowoff

The logarithmic plot of blowoff velocity as a function of pressure at constant burner diameter is seen to be a straight line approximately parallel to the corresponding flashback-velocity curve. (See fig. 3.) As was the case for flashback, therefore, the blowoff data are correlated in terms of the critical-boundary-gradient concept, where the parameter is similar to that in equation (5) (see also ref. 13):

$$g^{*}_{bo} = \frac{0.023}{D} R^{0.8}\overline{V}_{bo}$$

The pressure exponent for the curve of critical blowoff gradient $\frac{\partial \log g^{*}_{bo}}{\partial \log p}$ is found from figure 3 to be 1.85.

In view of the correlation of stability data with g^* as shown in figure 3, it is felt that extrapolation of the flashback and blowoff curves to higher working pressures can be done with some confidence.

COMPARISON WITH OTHER RESULTS

All existing data, for both the laminar and turbulent flames, are plotted in figure 4 for the purpose of comparison and for the delineation of stability boundaries. Shown in this figure are: the turbulent-flame data of figure 3; critical boundary velocity gradients calculated from the laminar and turbulent data presented in reference 5; stable laminar-flame data obtained from references 4, 8, and 14; and critical boundary velocity gradients calculated from the laminar data obtained in the investigation described in the appendix.

Flashback

The laminar data shown in figure 4 with pressures equal to or greater than 1 atmosphere contain points representing both flashback (ref. 5) and stable flames (refs. 4, 8, and 14). The flashback points show a consistency except for the point at 1 atmosphere. It can be seen from figure 4 that the flashback gradient at 1 atmosphere is larger than the gradient of the stable flame. However, it is to be expected that at the same pressure the experimental velocity gradients for the stable flame should be greater than the critical flashback value. Therefore, the laminar flashback curve was drawn only through the data of reference 5 above 1 atmosphere, and extrapolation of this curve to 1 atmosphere then results in a value of critical flashback gradient which is lower than the gradients obtained from the stable-flame data (as would be expected) and probably represents a good approximation to the actual value of g^*_{fb} at this pressure. (The 1-atmosphere point of ref. 5 remains a question; possibly some factor was present to induce premature transition.) The value of the pressure exponent for the laminar critical boundary velocity gradient is found from figure 4 to be very close to that found previously for the turbulent case. Similar results have been observed for many premixed flames (refs. 12, 13, and 15) and an explanation for such occurrence is given in reference 15.

A possible explanation for the varying slopes and position of the low-pressure (that is, 0.01 to 0.1 atmosphere) critical flashback data is advanced in the appendix in terms of decreased heat transfer, turbulence, and non-fully-developed inlet flow.

Transition

The value of g^*_{fb} obtained in reference 5 at 4.3 atmospheres is not correlated with either the laminar or turbulent flashback curves. The Reynolds number of the gas stream at this flashback point was such that the flow was probably within a transition region - changing from laminar to turbulent flow. It has been found that for many flames within this transition region, increasing the Reynolds number of the gas stream causes the flame to flash back at higher values of critical gradient, but the pressure at which flashback occurs remains unchanged (ref. 13). It has also been noted in reference 12 that such flame behavior occurred approximately within the same Reynolds number range as cold-flow transition. It is therefore felt that the value of flashback obtained in reference 5 at 4.3 atmospheres is a transition point; little can be said concerning the meaning of the value of critical flashback gradient here because of the difficulty in assigning the proper value to the friction factor in the transition regime.

Effect of Surrounding Atmosphere

The composition of the atmosphere surrounding a flame has been shown to have a great effect on the blowoff stability limits (ref. 9). It would be expected, however, that the critical flashback gradients would be unaffected by the surrounding atmosphere. Experimental data presented in reference 9 indicate that the composition of the atmosphere surrounding a flame has no effect on the critical flashback gradient. The experimental setups of reference 5 and the present work were similar (both used water-cooled copper burners) except that in the present work the exhausting hot combustion products were throttled in order to obtain the required chamber pressure, while in reference 5 a varying amount of cool inert gas (argon) was injected into the combustion chamber to obtain the necessary pressure. Thus, the important differences between the experiments of reference 5 and the present work are the composition and the temperature of the gases surrounding the flame. If it is accepted that the composition does not affect the flashback gradients in these cases (as in ref. 9) then any differences in these sets of data would be presumed to be caused by the temperature variance of the two setups. However, as seen in figure 4, the values of the critical flashback gradient obtained with both setups are almost equal for the turbulent flame. Therefore, it is believed that the temperature of the atmosphere surrounding the flame also had no effect on the flashback stability limits of the cyanogen-oxygen reaction.

Use of Stability Data for Burner Design

For a given flow regime, the region between the critical flashback and blowoff boundary velocity curves represents the stable burning region for the stoichiometric cyanogen-oxygen flame. Thus, in designing a burner to make use of this reaction, care must be taken so that at the operating conditions the calculated value of the boundary velocity gradient falls in the stable burning region.

CONCLUSIONS

The stability characteristics of a stoichiometric cyanogen-oxygen flame were studied over a pressure range of 40 to 200 lb/sq in. abs. Flashback and blowoff velocities were determined and the data correlated by the critical-boundary-gradient theory.

The pressure exponent of g^*_{fb} was found to be 1.97 and the pressure exponent of g^*_{bo} was 1.85. From comparison with reference data, it is believed that the temperature of the atmosphere surrounding the flame had no effect on the flashback stability limits.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 16, 1962.

APPENDIX

THE CYANOGEN-OXYGEN FLAME AT LOW PRESSURE

For many magnetohydrodynamic experiments it is desirable to have a plasma source at very low operating pressures. Therefore, Mr. Philip R. Maloney of the Magnetoplasmadynamics Branch undertook a study of the laminar cyanogen-oxygen flame in the pressure region of 0.01 to 0.1 atmosphere with a view towards such a use of this flame. Some of the results are presented herein. At the time of these experiments virtually nothing was known about the pressure dependence of the stability limits of the cyanogen-oxygen flame, and accordingly efforts were directed toward producing a stable flame at this pressure rather than in making a laminar-flame stability study per se. While these low-pressure stability data do not agree quantitatively with the extrapolated laminar-flame data obtained at higher pressure, the data are none the less qualitatively compatible with the high-pressure data and are self-consistent.

Figure 5 is a schematic diagram of the burner assembly. The burner tubes were uncooled and were fabricated of pyrex. A radiation shield served to prevent heating of the burner and the gas upstream by blocking off radiation from the flame. This shield was made up of a number of water-cooled pipes traversing the flow.

Figure 6 presents the flashback and blowoff velocities plotted against pressure and shows the stability loops of the nearly quenched flame.

The critical boundary velocity gradients for this pressure regime have already been presented in figure 4. The data for each length-diameter ratio of the burner were plotted separately since it was believed that the velocity profiles were different for each burner. Proper application of the friction factor in the critical-boundary-velocity-gradient theory requires the velocity profile of the gas stream to be fully developed. With increasing length-diameter ratio the gas-stream velocity profile approaches that of the fully developed flow; for these low-pressure experiments, the required parabolic velocity profile would have necessitated a length-diameter ratio of about 12 (ref. 16). From figure 4 it is seen that $\dfrac{\partial \log g^*_{fb}}{\partial \log p}$ increases with increasing length-diameter ratio; at the largest value of l/D, equal to 9.9, the pressure exponent of g^*_{fb} was found to be 1.77. This value approaches that obtained from the high-pressure laminar flashback stability data of reference 5, which, in turn, is about equal to that of the present high-pressure turbulent results.

A straight-line extrapolation of the high-pressure laminar flashback stability data of figure 4 to low pressure will show that the low-pressure stability data (that is, values of g^*_{fb}) are higher by a factor of 10. Possible explanations for this difference are: (1) the burners used for the low-pressure experiments were uncooled, (2) these burners were made of a material with a low thermal conductivity, (3) these burners, because of their small length-diameter ratio, had relatively flat velocity profiles (non-fully-developed), and (4) turbulence may have been produced by radiation shields. Conditions (1) and (2) would be expected to yield higher values of g^*_{fb} than those obtained from water-cooled burners fabricated of copper (ref. 17), such as the burners of reference 5 and the burners of the high-pressure investigation of the present paper, because of decreased heat transfer (higher wall temperatures). Effects of condition (3) are uncertain, but (4) would appear to yield values of critical flashback gradient which are also higher than those which would be obtained for smooth laminar flow. Considering these factors, therefore, the low-pressure results obtained by Mr. Maloney seem to be qualitatively compatible with the high-pressure laminar data. The arguments used for any quantitative comparison of the two sets of data would require tip temperature measurements and determination of the effects on the flow field of (1) the small length-diameter ratios and (2) the turbulence-producing radiation shield and flashback arrester.

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TABLE I.- FLAME STABILITY DATA

Flashback								Blowoff							
Flashback pressure, psia	Flashback pressure, atm	Burner diameter, in.	Velocity, ft/sec	g^*_{fb}, sec^{-1}	t_m, ^oF	p_o, psia	R	Blowoff pressure, psia	Blowoff pressure, atm	Burner diameter, in.	Velocity, ft/sec	g^*_{bo}, sec^{-1}	t_m, ^oF	p_o, psia	R
39	2.65	0.1	46.3	2.4×10^5	80	95	1.22×10^4								
42	2.86		48.9	2.88			1.39								
45	3.06		51.4	3.25			1.55								
53	3.61		53.2	3.91			1.89								
56	3.81		57.1	4.68			2.15								
60	4.08	.094	85.3	8.87			2.9								
68	4.63		90.6	1.1×10^6			3.52								
74	5.03		93	1.23			3.92								
78	5.31		92.6	1.32			4.3								
88	5.99	.073	124	2.30	170	315	4.1	29	1.97	0.073	374	6.47×10^6	170	315	4.05×10^4
97	6.66		130	2.77			4.88	33	2.24		381	7.85			4.73
105	7.14		137	3.16			5.41	37	2.52		388	8.96			5.39
115	7.82		150	4			6.47	43	2.93		400	1.04×10^7			6.42
150	10.2	.052	176	7.11			7.06	55	3.74	.052	480	1.94			7.05
170	11.6		182	8.33			8.24	60	4.08		517	2.37			8.27
190	12.9		192	9.83			9.58	68	4.63		548	2.81			9.48
158	10.8		180	6.9	192	415	6.62	60	4.08		475	1.83	192	415	6.61
200	13.6		199	9.75	192	415	9	72	4.90		540	2.73	192	415	9.03

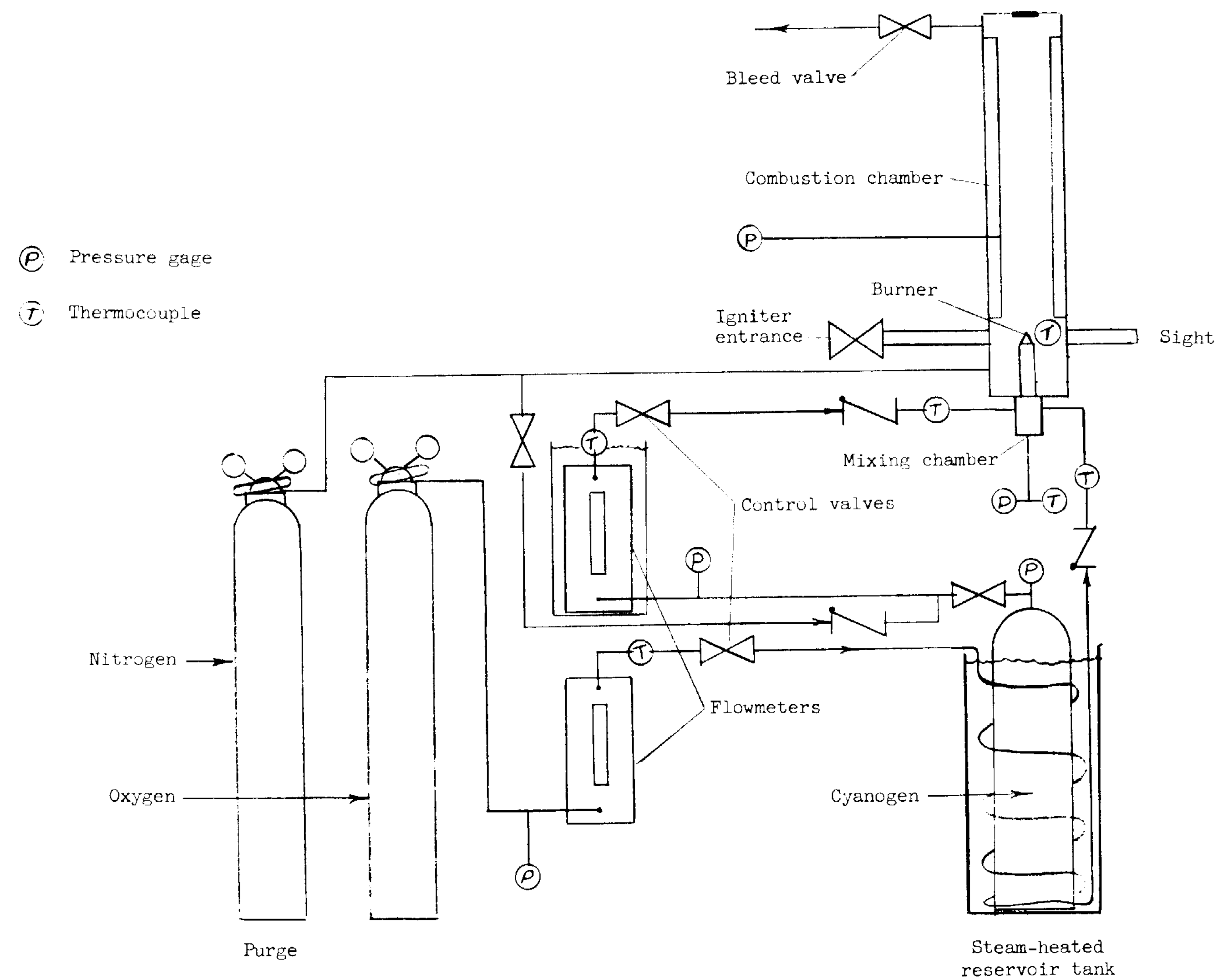
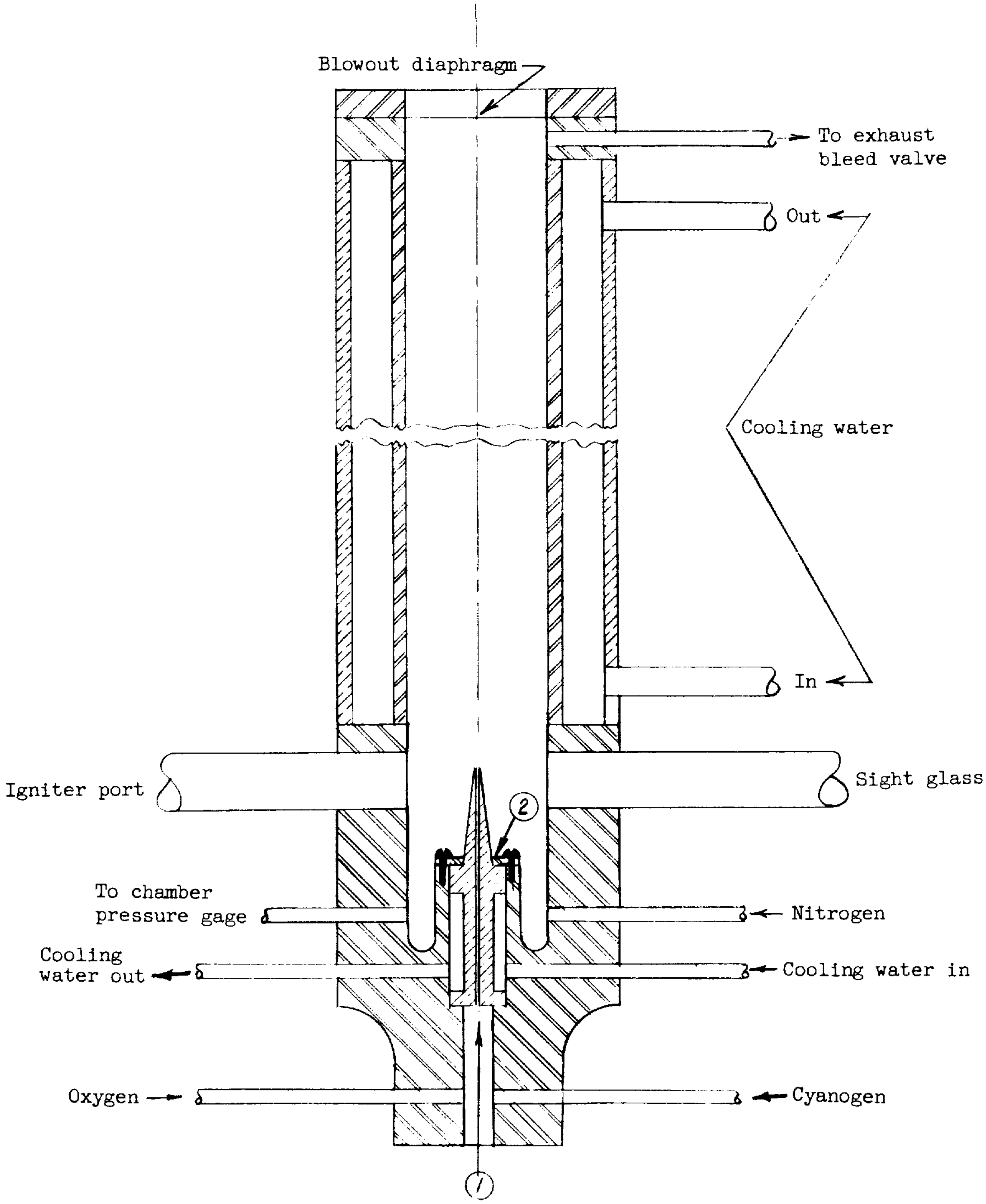


Figure 1.- Schematic diagram of high-pressure cyanogen-oxygen burner.



Thermocouples located at points 1 and 2

Figure 2.- Combustion chamber.

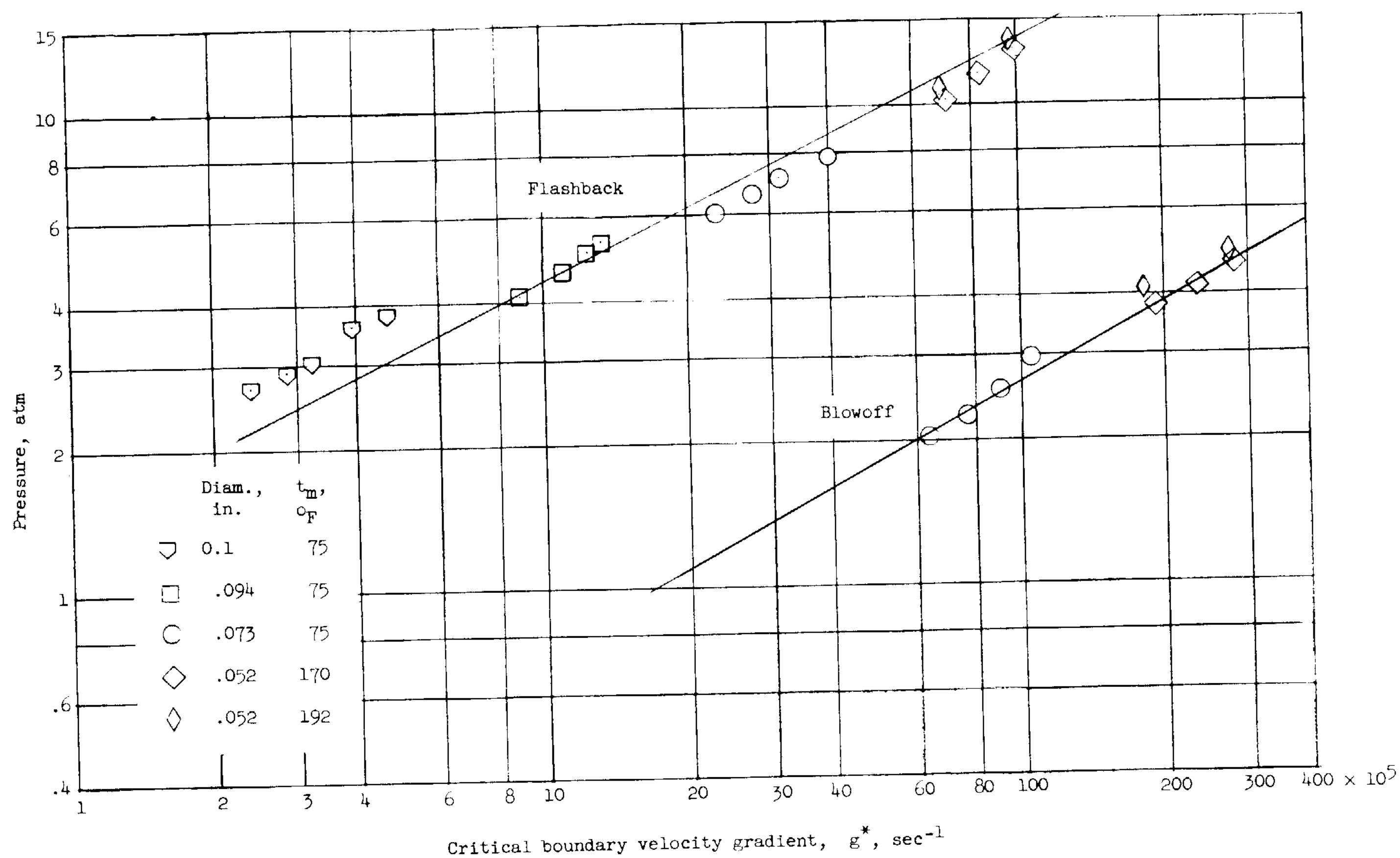


Figure 3.- Stability limits of the turbulent cyanogen-oxygen flame.

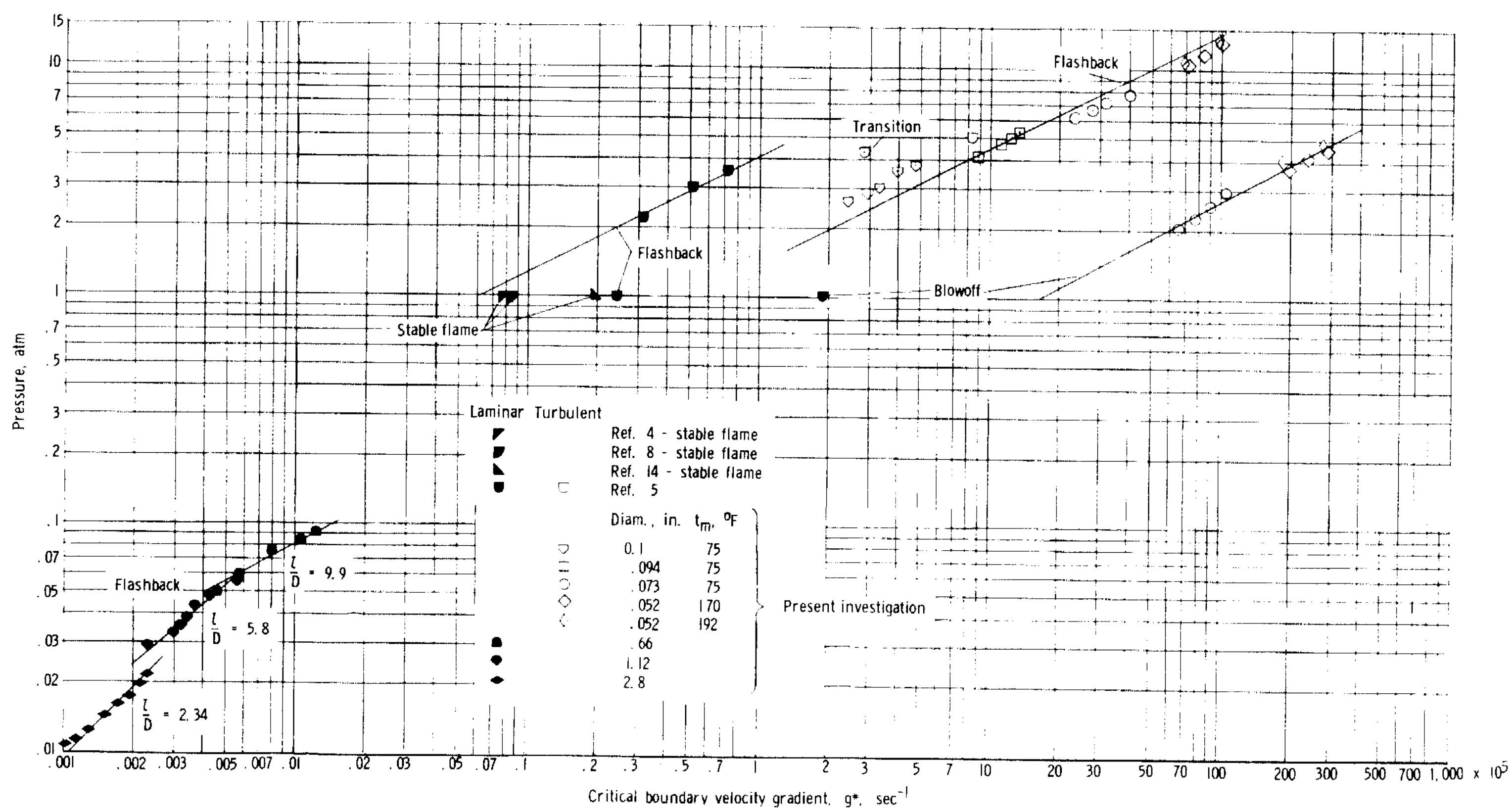
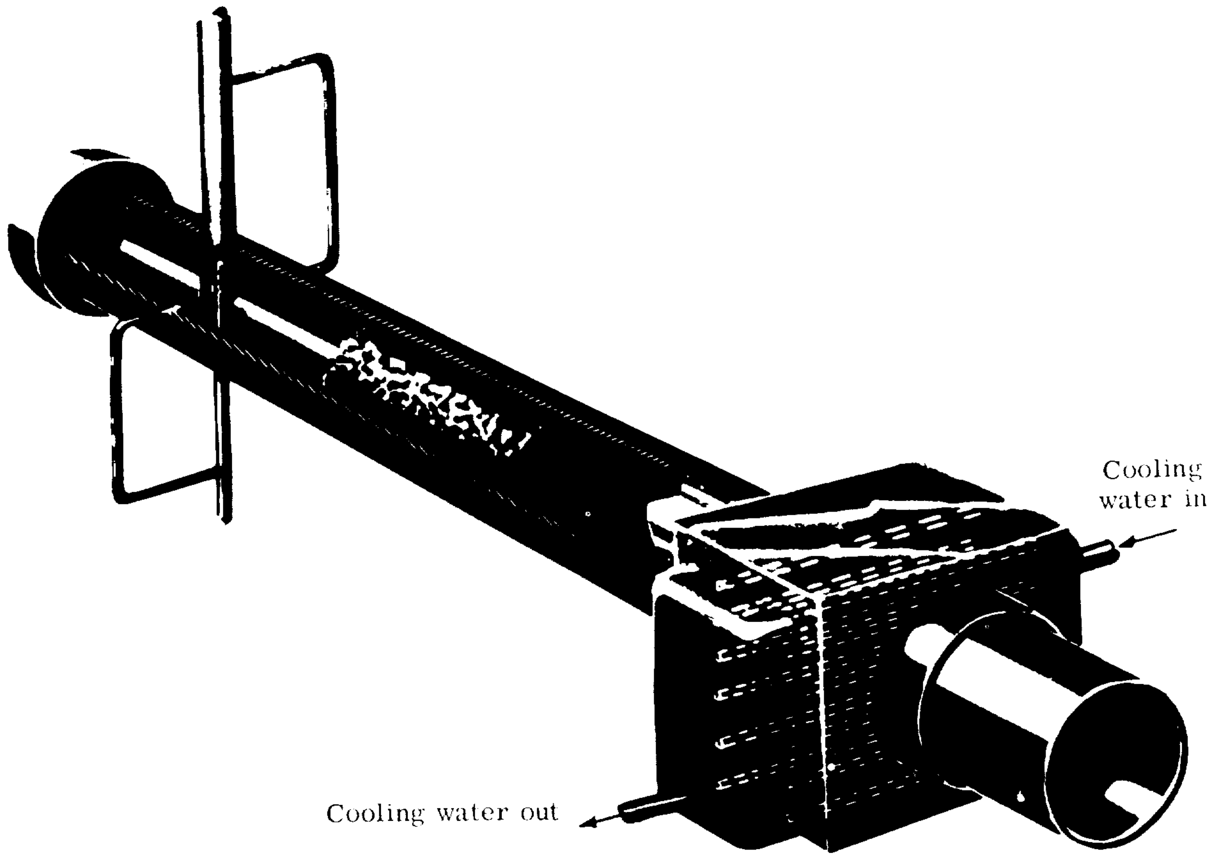


Figure 4.- Stability limits of the cyanogen-oxygen flame.



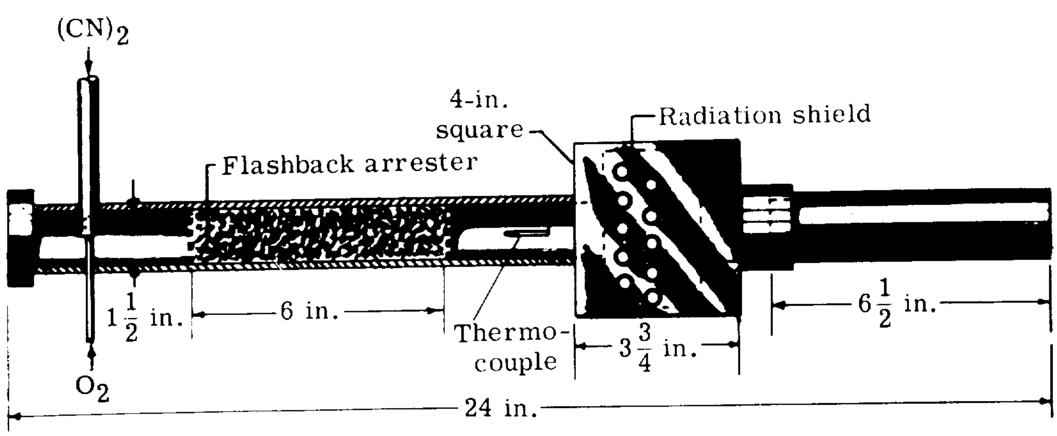


Figure 5.- Low-pressure burner.

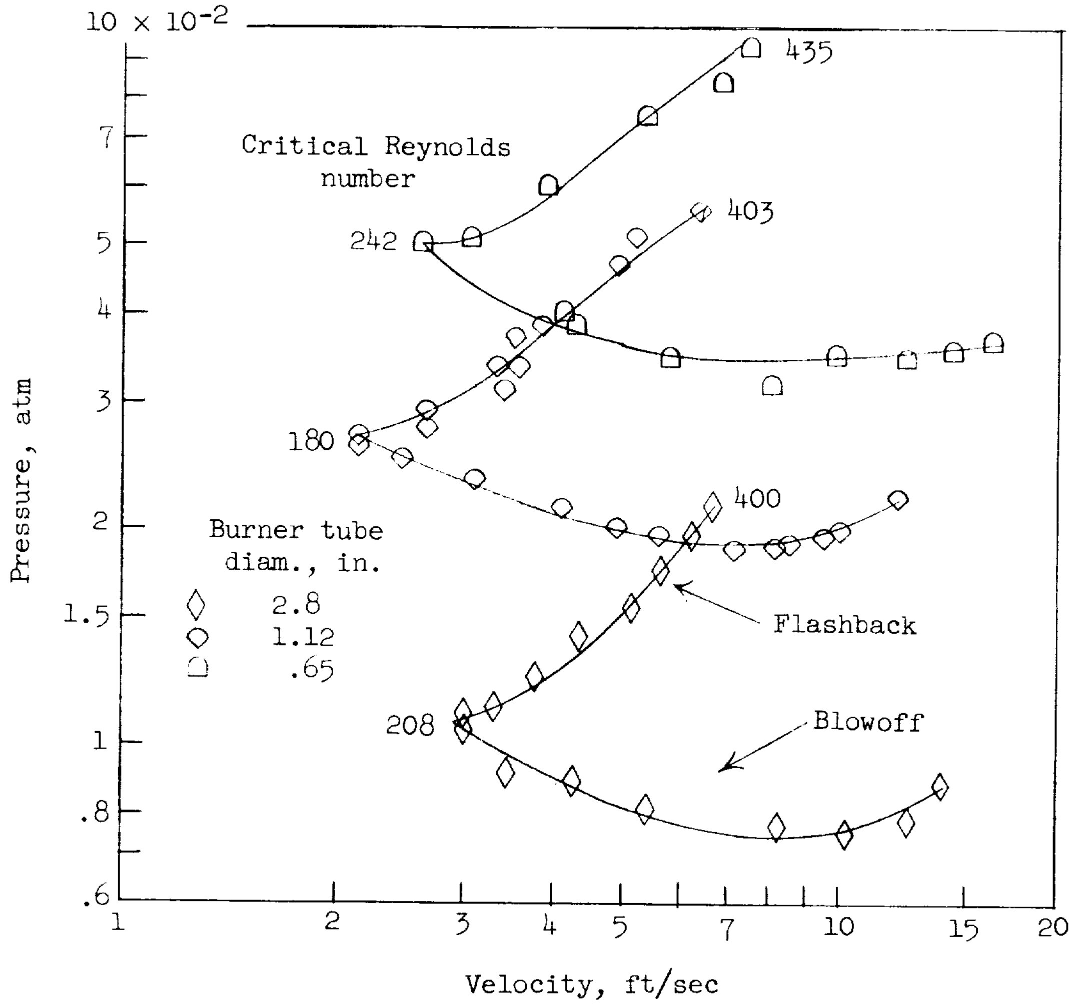


Figure 6.- Critical flashback and blowoff velocities for the cyanogen-oxygen flame.